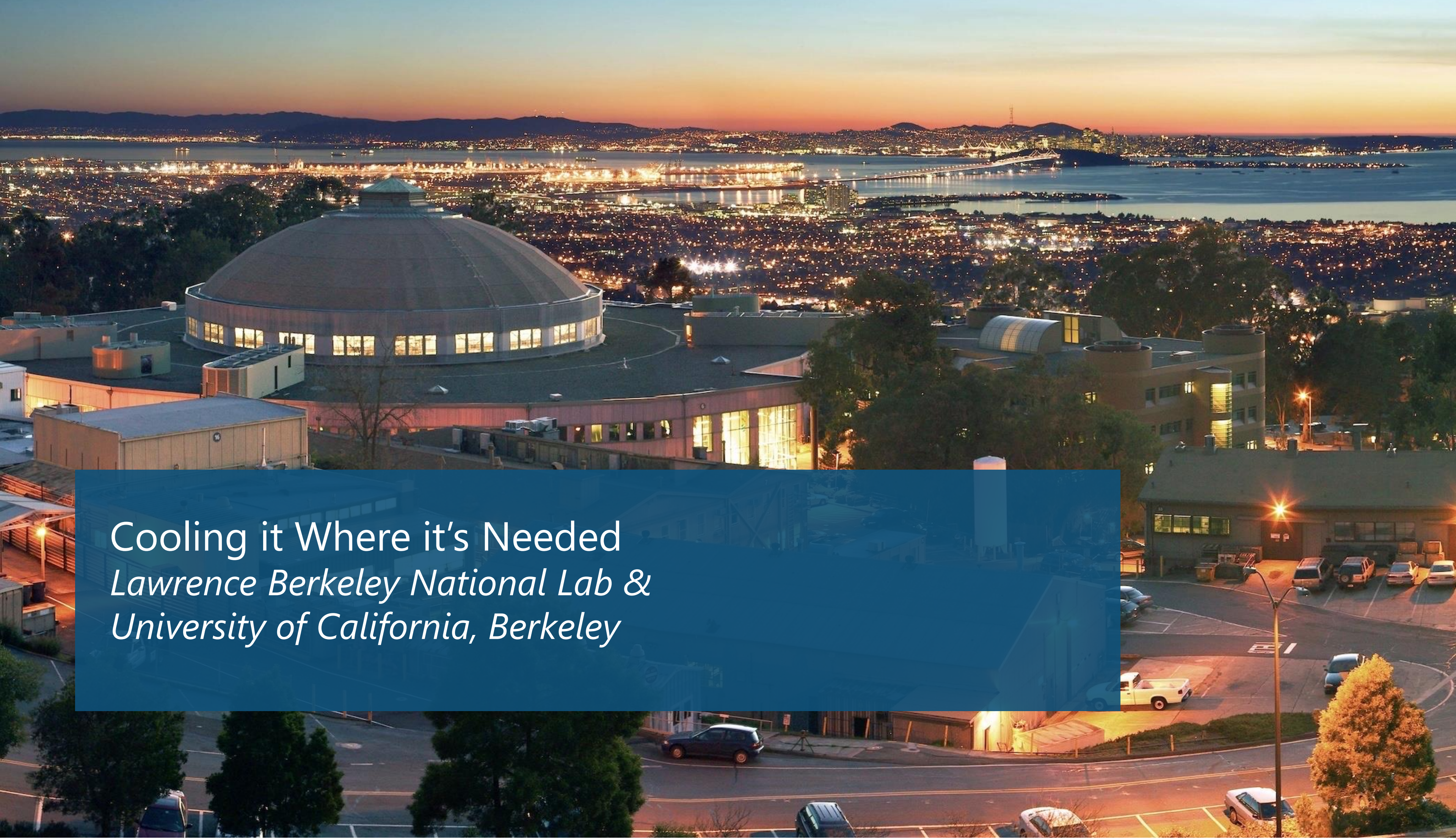


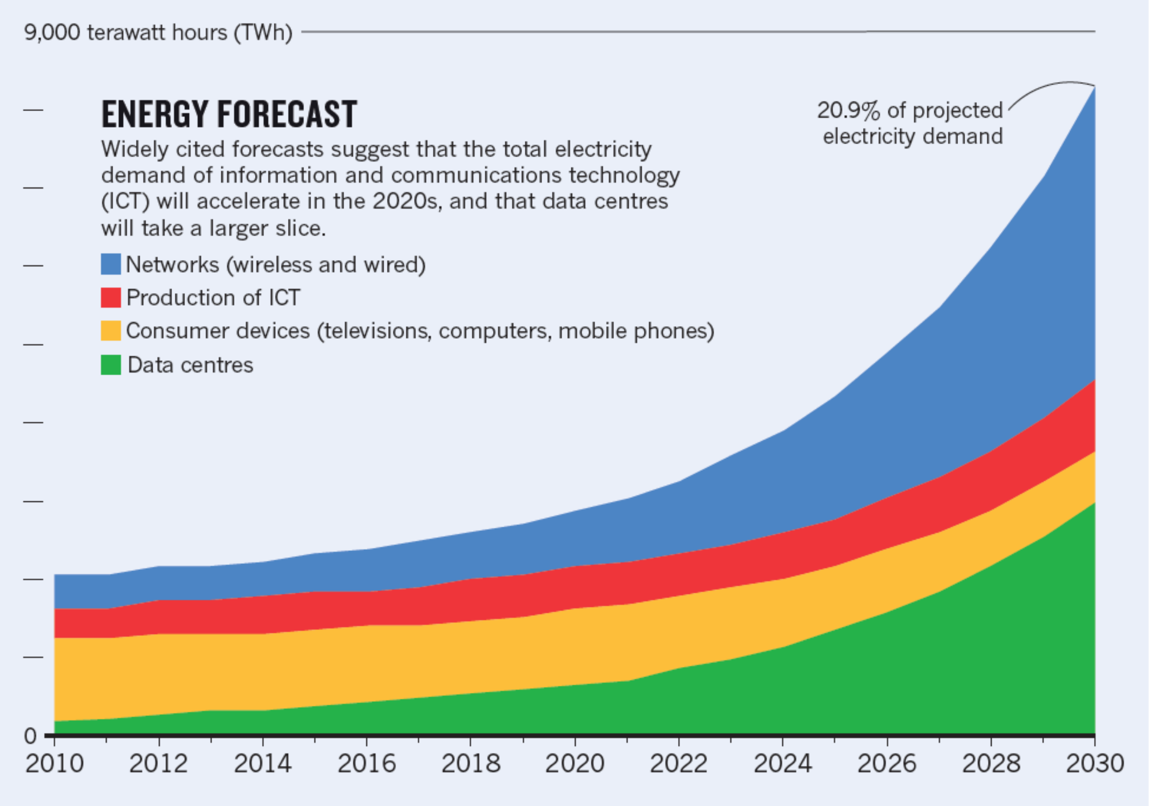
Cooling it Where it’s Needed

Lawrence Berkeley National Lab &
University of California, Berkeley

BERKELEY LAB

ENERGY TECHNOLOGIES AREA

Energy Forecast For Data Centers



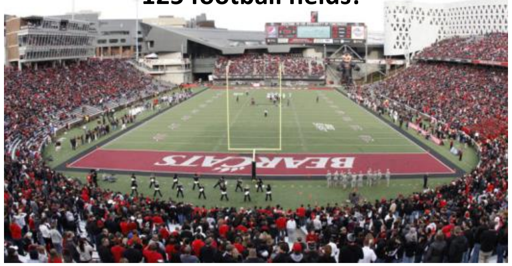
The chart above is an 'expected case' projection from Anders Andrae, a specialist in sustainable ICT. In his 'best case' scenario, ICT grows to only 8% of total electricity demand by 2030, rather than to 21%.

164 | NATURE | VOL 561
2018

Data Centers Can be Very Big

1- Switch – The Citadel
Location: Reno Nevada
Area: 7,200,000 Sq.Ft.

125 football fields!



2- Range International Information Group
Location: Langfang, China
Area: 6,300,000 Sq.Ft.

110 football fields!

3- Switch – SuperNAP
Location: Las Vegas Nevada
Area: 3,500,000 Sq.Ft.

60 football fields!

100s MWs – GW

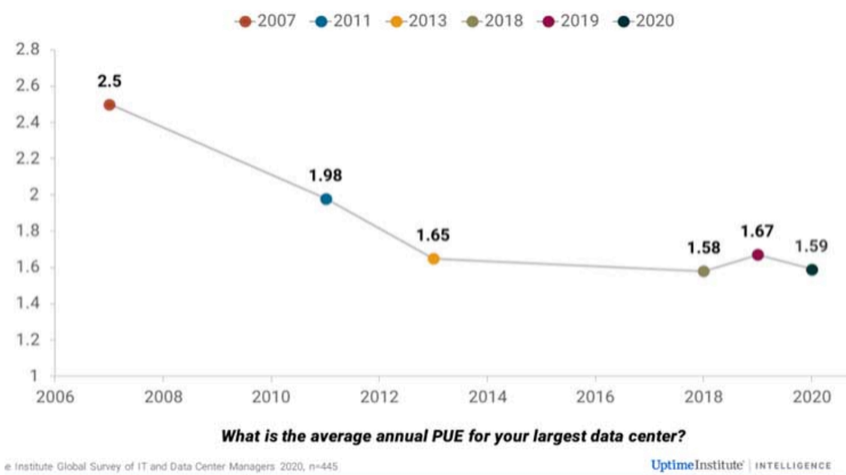
Energy in- Hot air out

Data Centers PUE leveling off at around 1.6 in US

PUE: Power Usage Effectiveness

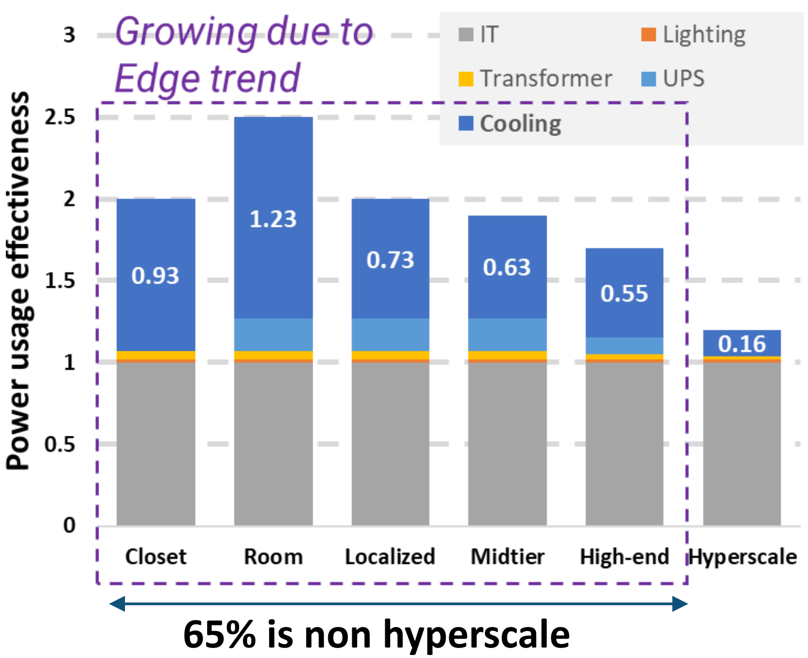
$$PUE = 1 + \frac{Non\ IT\ Facility\ Energy}{IT\ Equipment\ Energy}$$

2020 data



Ascierto, R., Lawrence, A., "Uptime Institute Global data center survey 2020", UII-38 v1.1, July 2020

PUE by Data Center Type (2014) US



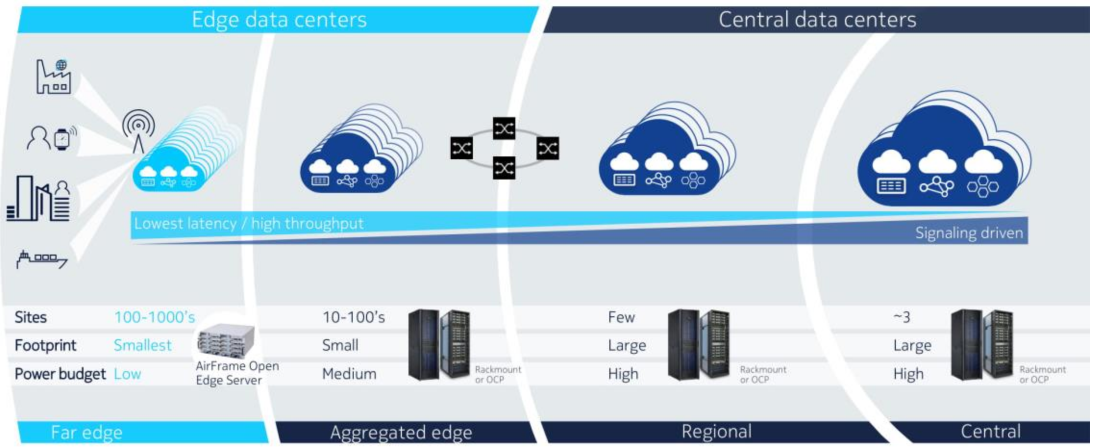
Thermal management represents **33-40% energy use** in non-hyperscale data centers

Courtesy, Dr. Peter Debock, ARPA-E

Growing importance of low latency secure data – Edge Computing

- The number of Edge Data centers serving <u>mission-critical</u> applications is expected to grow in 2020-2030

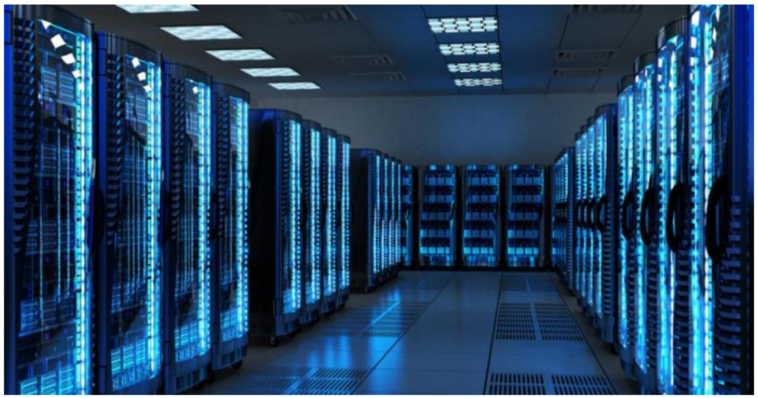
  - Smart Healthcare
  - Industry 4.0
  - Security applications
  - Smart Agriculture
  - Machine vision
  - Financial transactions
  - UAV/drone operations
  - 5G/6G
  - Self driving cars



Low Latency and security/compliance for mission critical applications requires data centers to be closer to their customers. This will drive more PUE>1.6 sites

Courtesy, Dr. Peter Debock, ARPA-E

Data Center Types



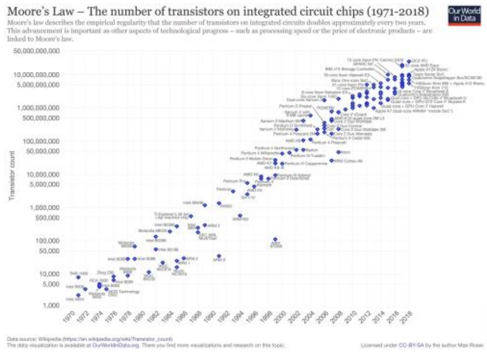
Hyperscale

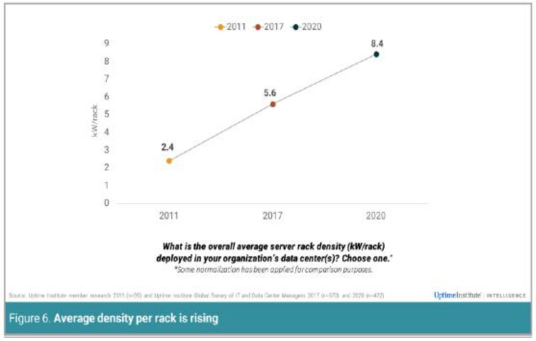
Edge

Why now? – inflection point

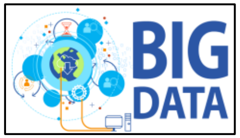
- Energy usage trend will go up
- At PUE 1.6 fixed and growth rate, US Data centers will grow to 900 billion kWh_{th} ~3.0 quads by 2028
- **Cooling load ~ 0.73 Quad**
  (60% non-hyperscale 40% thermal mgmt.)

1. Moore's law sunsetting – need new tech solutions





2. Explosive growth

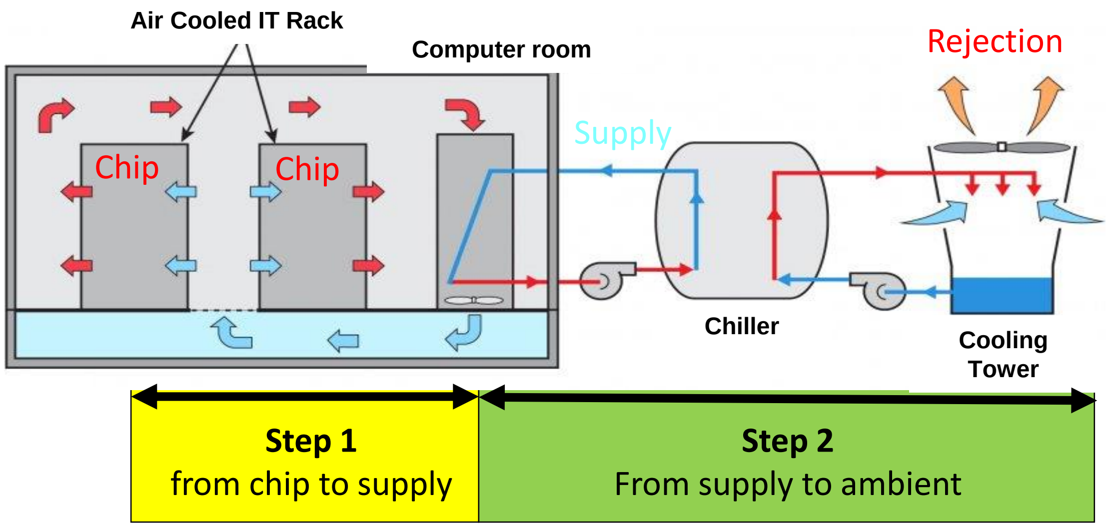


3. Edge Computing trend

Courtesy, Dr. Peter Debock, ARPA-E

Baseline data center – Inefficient Heat Transfer from Chip to Supply

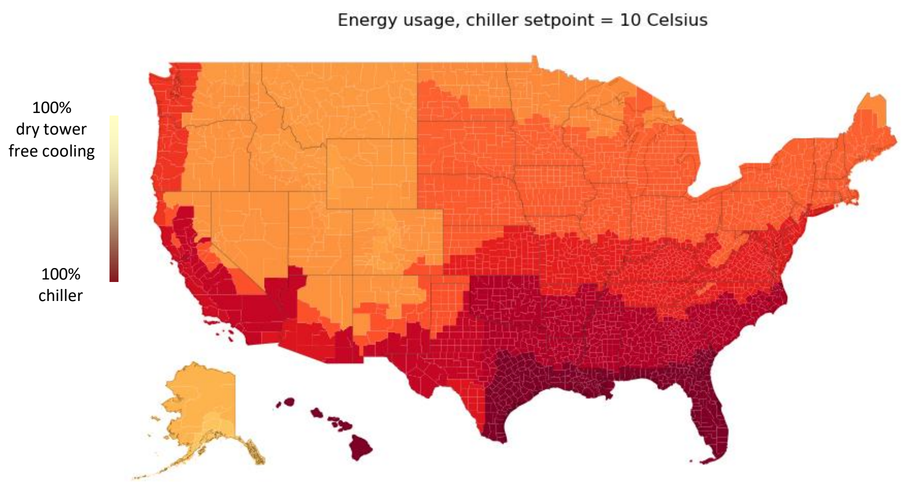
- Consider two cooling steps
- Step 1: chip (90C), to air (40C), to
- Step 2: chiller
  to chiller rejection out (50C)

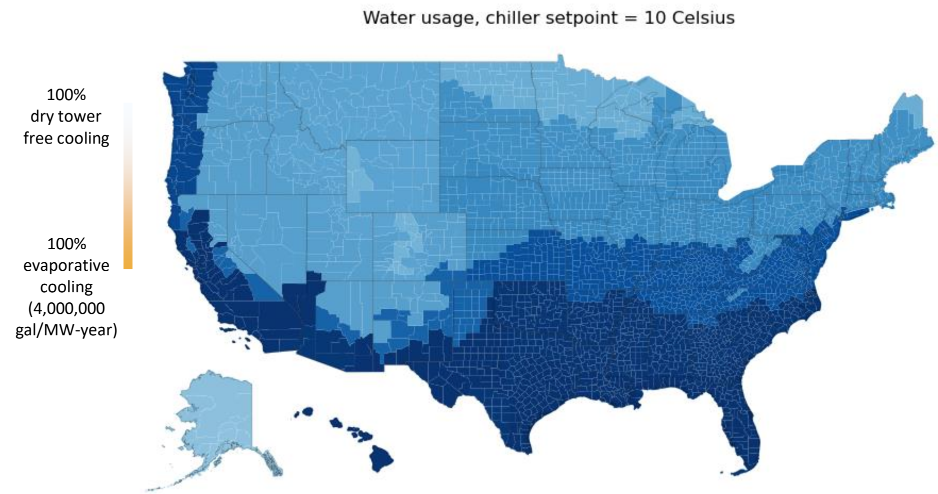


In spite of positive temperature difference between the chip and the ambient heat pumping needed!

Courtesy, Dr. Peter Debock, ARPA-E

Inefficient Heat Transfer Drives Excessive Energy / Water use





- The price paid for the standard supply temperature (10°C) is **Inefficient Cooling = Excessive Energy Use**
  - Chiller has to run most of the year – 0.75 quads for cooling
  - Water is consumed in most locations – *approx. total of 1591 billion gallons of water use was attributable to US data centers*

https://www.nature.com/articles/s41545-021-00101-w

Courtesy, Dr. Peter Debock, ARPA-E

LOW GWP Refrigerants: Compromise between safety, energy efficiency and capital cost

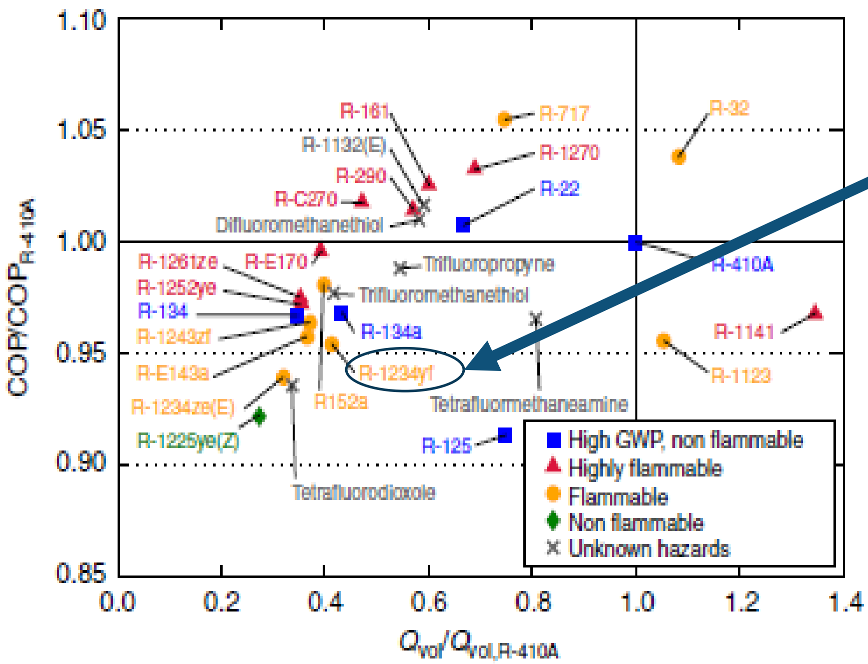


Figure 3 | Coefficient of performance and volumetric capacity of selected low-global-warming-potential fluids. Results are shown for the basic vapour compression cycle; values are relative to those for R-410A and are calculated with the 'optimized' cycle model.

Low Q_{vol} means larger equipment: Higher cost

- Slated to be the replacement for R-134a in automobiles in EU, Japan and USA
- Natural Refrigerants are the replacement for large scale systems (e.g. Supermarket)
- The middle ground, in terms of system size and complexity—for example, residential central air-conditioning systems—is where the greatest debate on refrigerant choice occurs.

Limited options for low-global-warming-potential refrigerants

Mark O. McLinden[1], J. Steven Brown[2], Riccardo Brignoli[3], Andrei F. Kazakov[1] & Piotr A. Domanski[3]

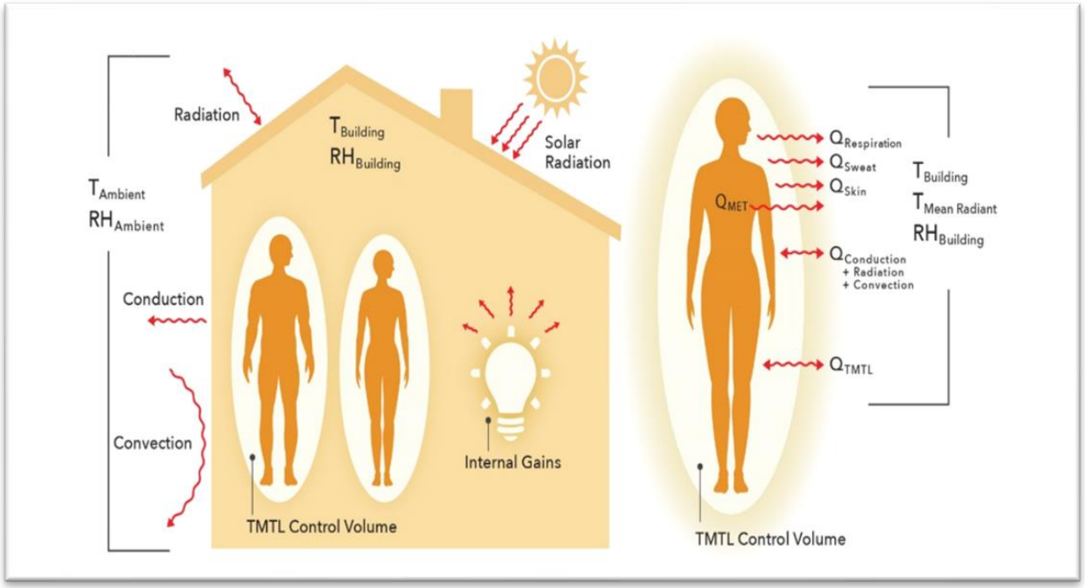
NATURE COMMUNICATIONS | 8:14476 | DOI: 10.1038/ncomms14476 | www.nature.com/naturecommunications

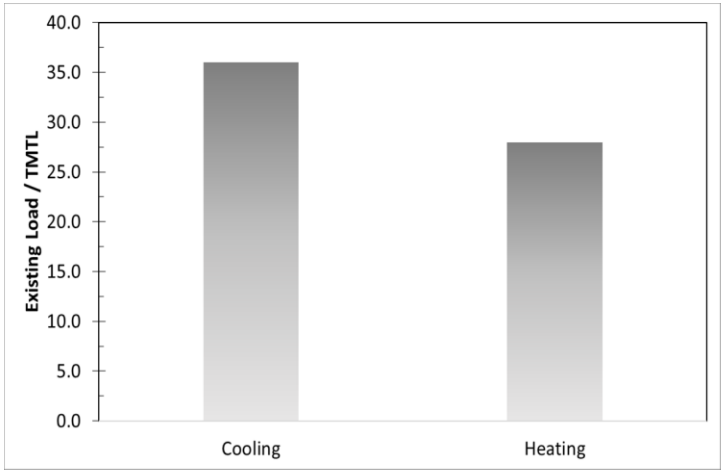
CellPress Joule

Perspective

Theoretical Minimum Thermal Load in Buildings

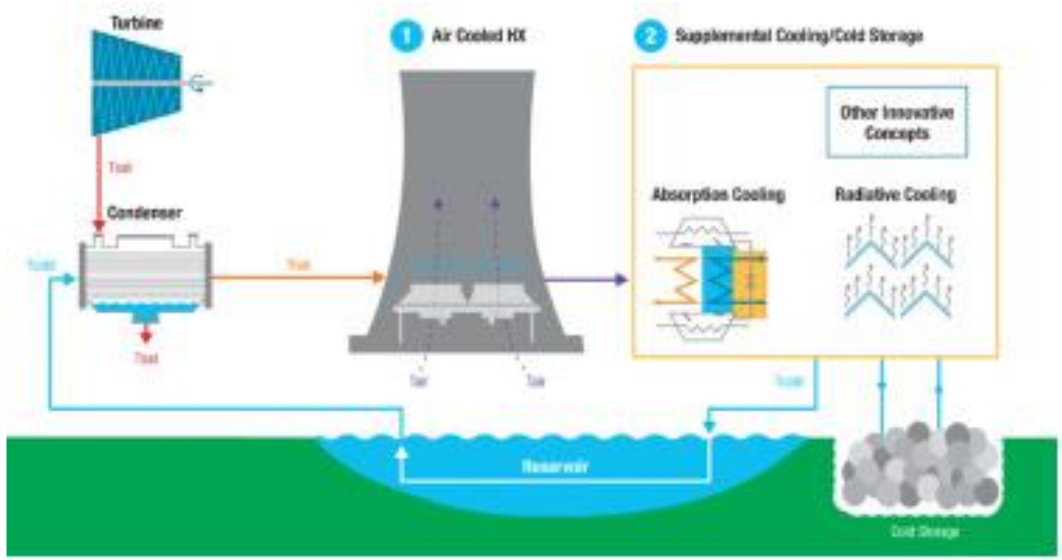
Chuck Booten,[1,4] Prakash Rao,[2,4] Vi Rapp,[2,4] Roderick Jackson,[1] and Ravi Prasher[2,3,*]





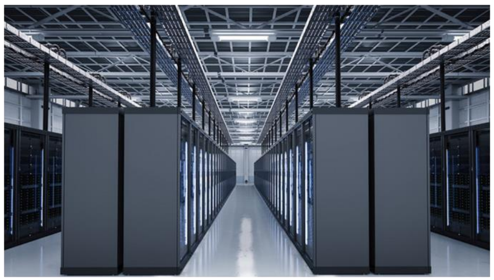
What is the TMTL for computer servers?

Ways to Approach TMTL: Thermal Storage +Radiative cooling

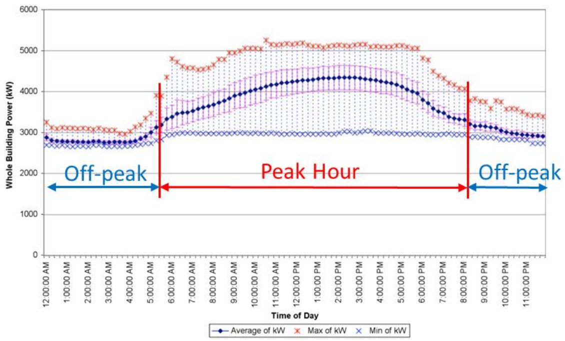


Stark and Klausner, Joule, 2017

Ways to Achieve TMTL: Moisture Battery

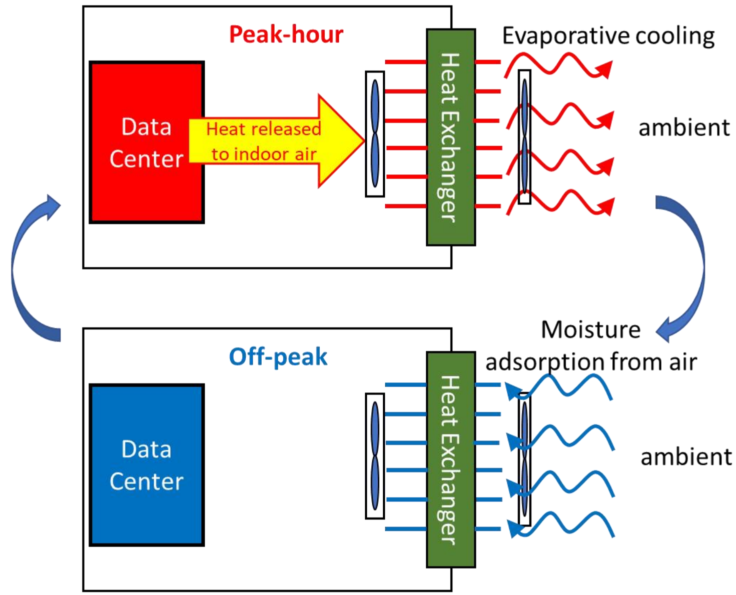


Typical Data Center Daily Load Shape in CA [1]



[1] Ghatikar, Girish, et al. *Demand response and open automated demand response opportunities for data centers.* No. LBNL-3047E. Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), 2009.

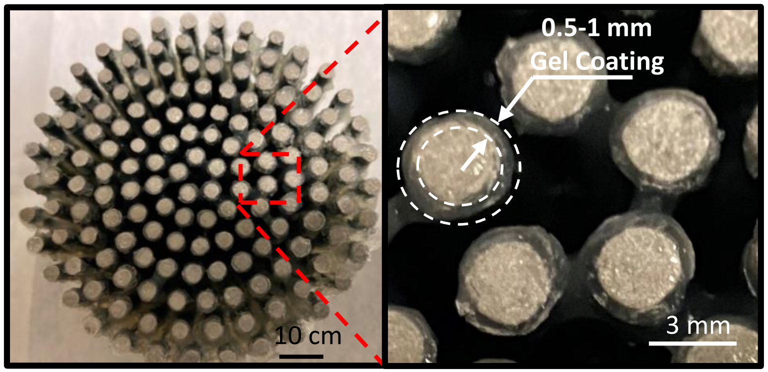
Principle of Sorption-Evaporation Passive Cooling

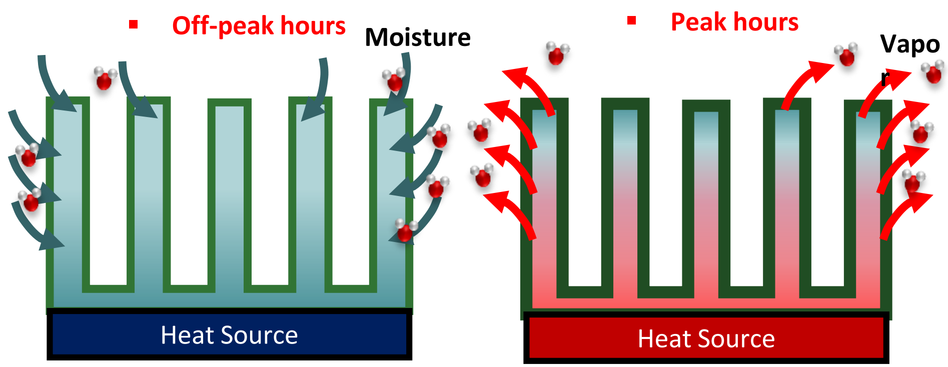


1) **Low energy consumption (only for pumping)**
2) **Zero water consumption (self-sustained water from absorption)**
3) **Moisture capturing and water storage**

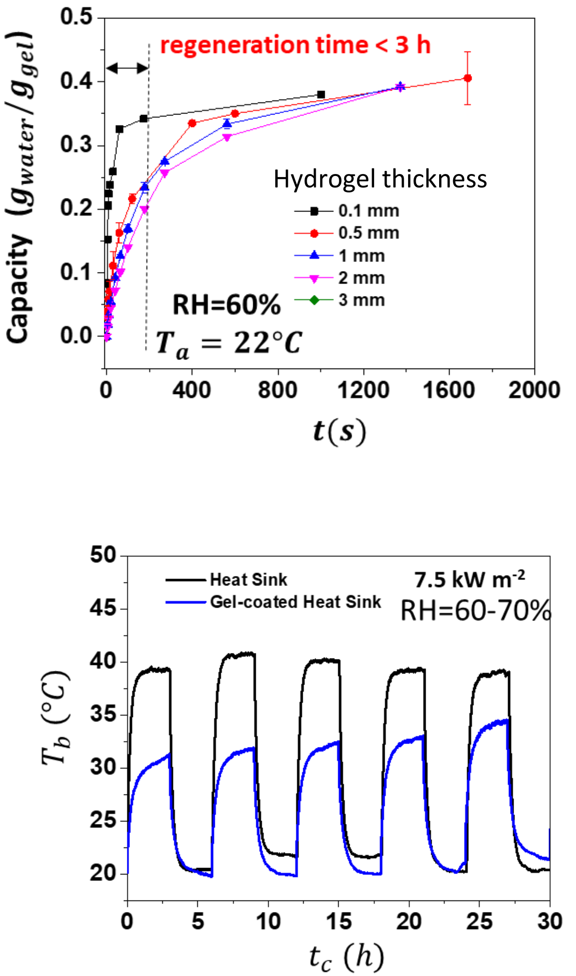
Moisture Battery

Example of Hydrogel Coating for Water Storage





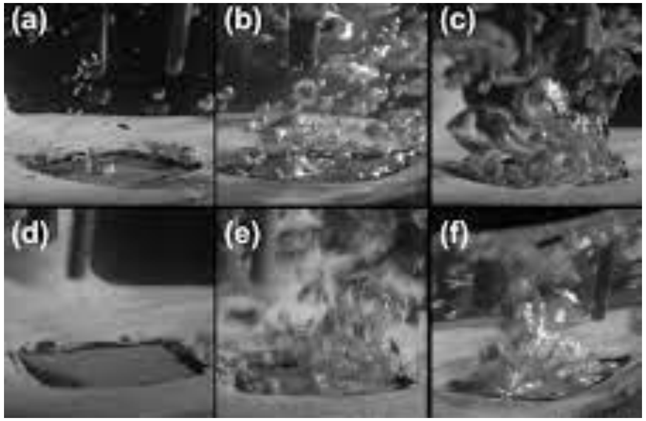
Moisture adsorption kinetics of hydrogel

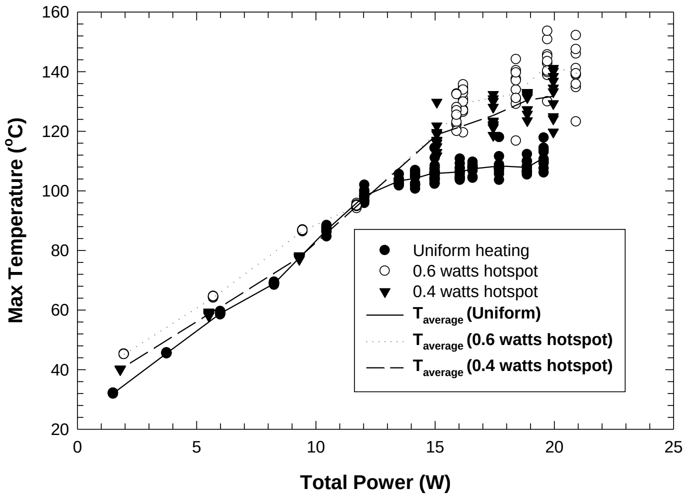


- Thin hydrogel coating on extended surface for fast evaporative cooling in the day-time (peak hours) and fast moisture adsorption at night (off peak hours).
- Fast adsorption kinetics (< 3 h) and high capacity (~ 1 g_{water} g_{gel}^{-1}) ensures the continuous operation.

Courtesy: Prof. Renkun Chen, UCSD

Ways to Achieve TMTL : Chip Scale Two Phase Cooling





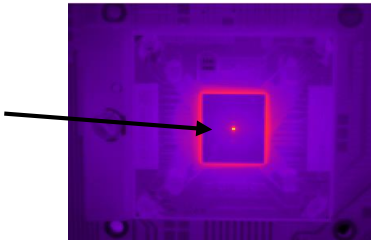
Challenges:

- **No temperature fluctuation in the single phase region**

- **Magnitude of temperature fluctuations increase with increasing hotspot power**

- **Temperature fluctuation as high as 40 oC observed**

Hotspot



Prasher and Chang

Proceedings of the Sixth International ASME Conference on Nanochannels, Microchannels and Minichannels ICNMM2008 June 23-25, 2008, Darmstadt, Germany

How Efficient is a Computer Chip?

	Theoretical Limit	SOA as % of Theoretical Limit
Heat Engine	Carnot	~30- 70
Solar PV	Shockley–Queisser	~70
Heat Pumps	Carnot	~30-50
Computer chip	Landauer	<<.01

Computer Chip is a heater!

Lets use it

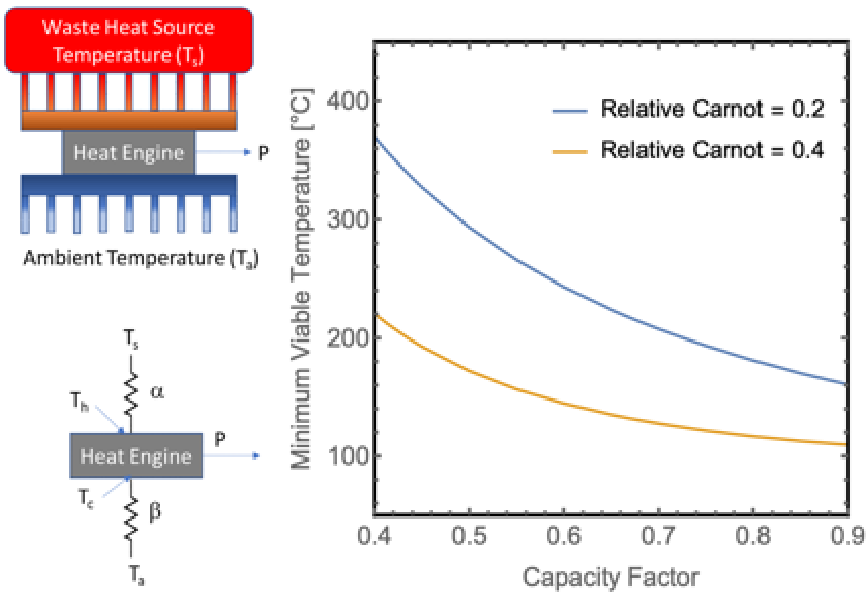
Combined computing and heating?

Joule
CellPress

Perspective

Techno-economic analysis of waste-heat conversion

Charles Geffroy,[1,4] Drew Lilley,[1,2,4] Pedro Sanchez Parez,[3] and Ravi Prasher[1,2,*]



$$\mathit{Cost\ of\ electric\ power} = \frac{\left(\sqrt{C_h} + \sqrt{C_c}\right)^2}{\left(\sqrt{T_s} - \sqrt{T_a}\right)^2} + C_{he}$$

Temperature of waste heat source

Waste heat conversion to electricity does not make sense for data centers

Using Heat as Heat

Applied Energy 258 (2020) 114109

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A review of data centers as prosumers in district energy systems: Renewable energy integration and waste heat reuse for district heating

Pei Huang[a], Benedetta Copertaro[a], Xingxing Zhang[a,*], Jingchun Shen[a], Isabelle Löfgren[a], Mats Rönnelid[a], Jan Fahlen[b], Dan Andersson[b], Mikael Svanfeldt[b]

[a] Department of Energy and Built Environment, Dalarna University, Falun 79188, Sweden
[b] EcoDataCenter, Falun 79170, Sweden

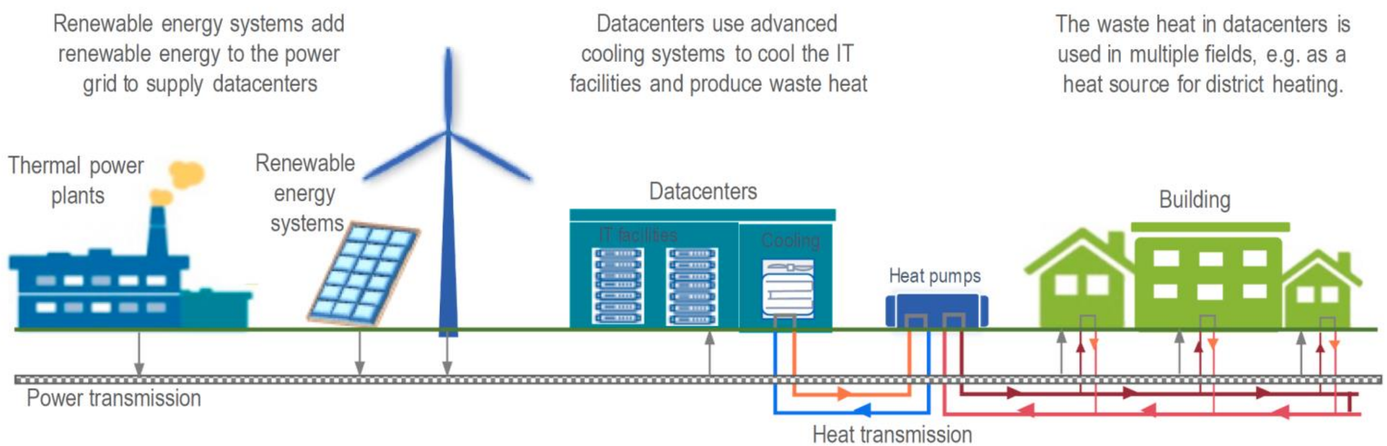


Fig. 1. Data centers as prosumers in the district energy systems.

Long Distance Transmission of Heat is a fundamental and applied challenge

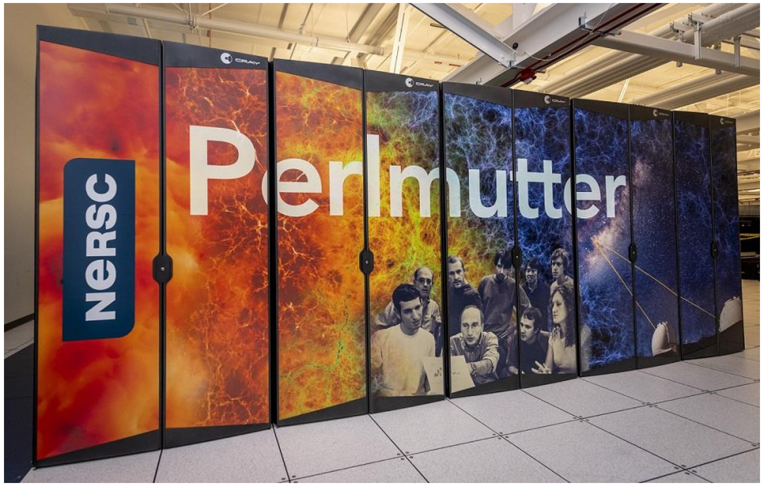
Five thermal energy grand challenges for decarbonization

Roughly 90% of the world's energy use today involves generation or manipulation of heat over a wide range of temperatures. Here, we note five key applications of research in thermal energy that could help make significant progress towards mitigating climate change at the necessary scale and urgency.

Asegun Henry, Ravi Prasher and Arun Majumdar

NATURE ENERGY | VOL 5 | SEPTEMBER 2020 | 635–637

Combined Computing & Heating at LBNL



- At Wang Hall, our primary supercomputing center, waste heat from the data center operating space is used to augment office space heating requirements.
- As computational demands increase and greater heat loads are rejected, district heating systems become viable. LBNL is in the planning phase of a district heating loop using the rejected heat from NERSC.

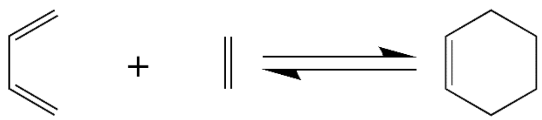
Backup

Increasing Heat Capacity of Thermal Fluids

- Most of the thermal liquids are van der Walls bonded molecule (<5 kJ/mol): low heat capacity

- Water has highest heat capacity. ~70% of heat capacity is due to H_2 bond breaking (~10 – 30 kJ/mol)

- Can we use Covalent bond breaking (> 100 kJ/mol)to beat water or achieve higher heat capacity for T >100 ^oC



Diels–Alder reactions (first proposed for thermal energy storage/transfer fluid by Lenz[1,2] and Sparks and Poling[3] in the late 1970s and early 1980s)

Thermodynamics:

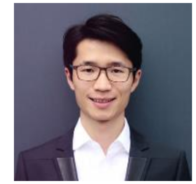
- High reaction enthalpy (ΔH_{rxn}) and entropy (ΔS_{rxn})
- Turning temperature is often moderate

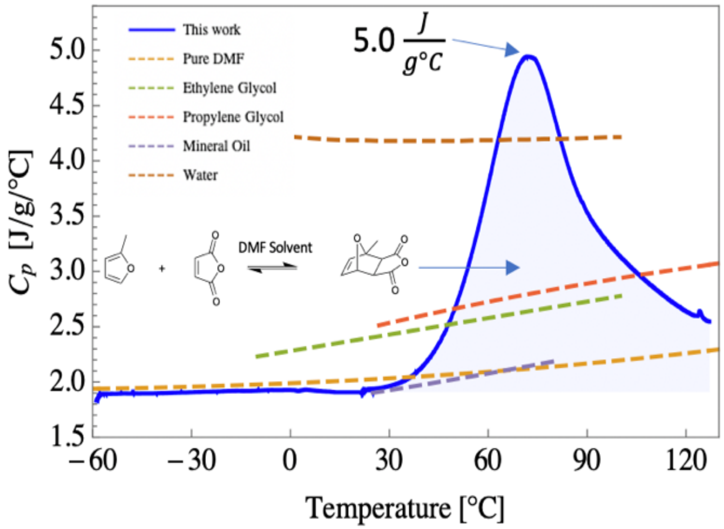
Additional benefits:

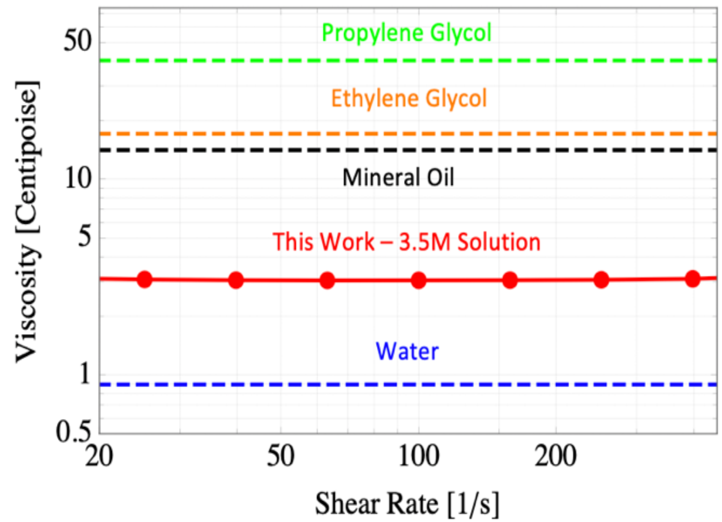
- These reactions have been widely studied
- They frequently occur in liquid phase

T. G. Lenz, L. S. Hegedus, and J. D. Vaughan, "*Int. J. Energy Res.*, vol. 6, no. 4, pp. 357–365, Jan. 1982.
B. G. Sparks and B. E. Poling, *AIChE J.*, vol. 29, no. 4, pp. 534–537, Jul. 1983.

Heat Capacity & Viscosity



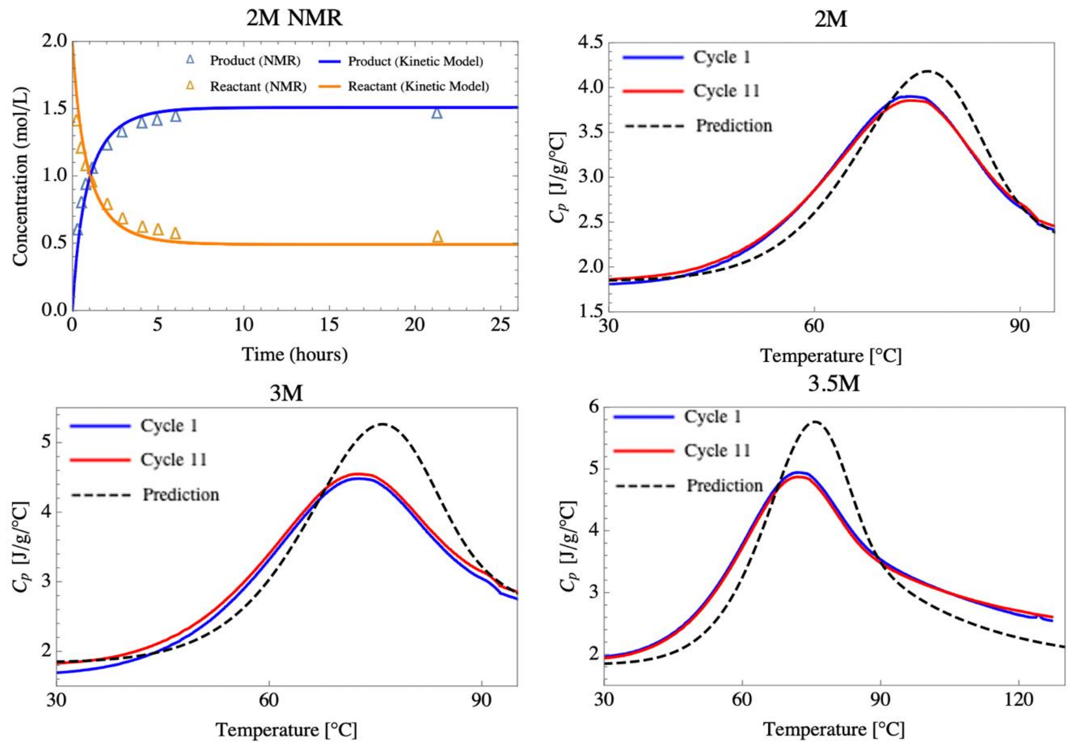




Effective heat capacity & Viscosity of 3.5M maleic anhydride and 2-methylfuran in DMF (solid blue) compared to the heat capacities of common thermal fluids (water, ethylene glycol, propylene glycol, mineral oil, and pure DMF).

To Appear in *iScience*

Comparison with DFT Predictions



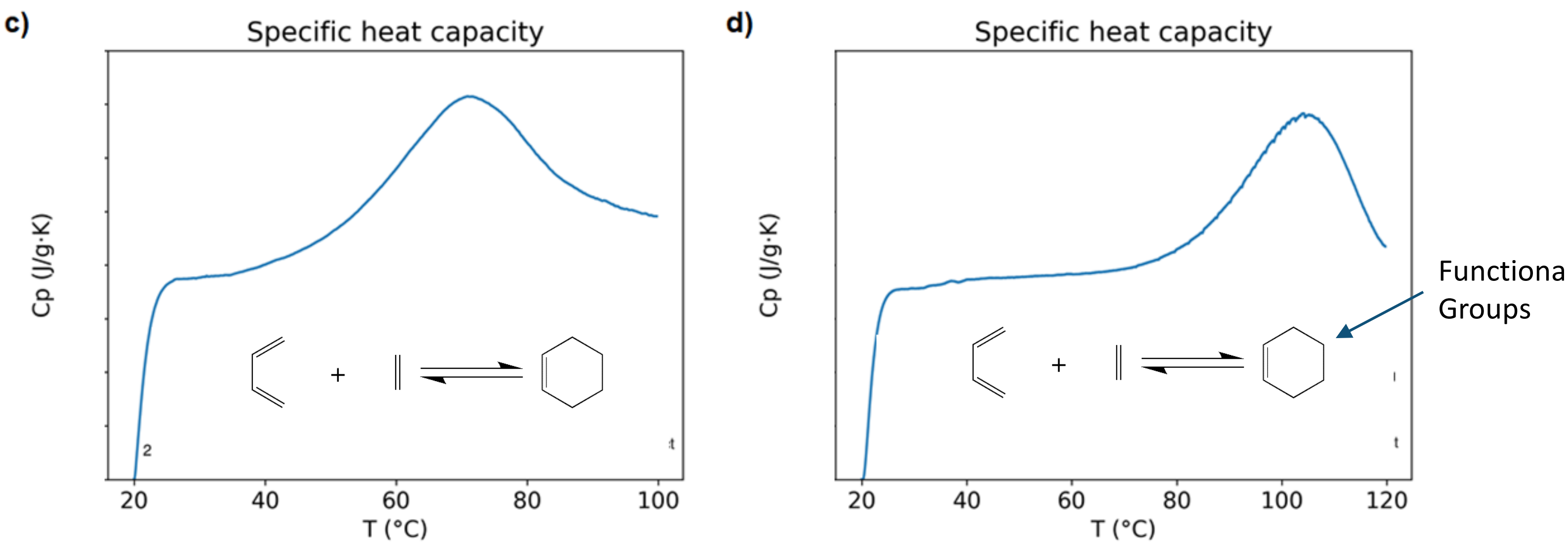
DFT

$$C_{p,kinetic}(T) = \frac{\Delta H_{rxn}}{\rho}\frac{dc}{dT} + C_{p,fluid}$$

DFT

Eyring equation for rate of reaction $\frac{k_b T(t)}{h} e^{-\frac{\Delta G_f}{RT(t)}}$

Static Tuning of Diels Alder Thermochemical Fluids Using Functional Groups



Peak heat capacity can be shifted